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Development of System Performance Model

Transmission of information by acoustic communication along metal pathways in nuclear facilities FY 2017 Annual Report

Nuclear Engineering Division

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ANL/NE-17/22

Development of System Performance Model

Transmission of information by acoustic communication along metal pathways in nuclear facilities FY 2017 Progress Report

prepared by
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ABSTRACT

The objective of this project is to develop and demonstrate methods for transmission of information in nuclear facilities by acoustic means along existing in-place metal piping infrastructure. Pipes are omnipresent in a nuclear facility, and penetrate enclosures and partitions, such as the containment building wall. In the envisioned acoustic communication (AC) system, packets of information will be transmitted as guided acoustic waves along pipes. Performance of AC hardware and network protocols for efficient and secure communications under development in this project will be eventually evaluated in a representative nuclear power plant environment.

Research efforts in the first year of this project have been focused on identification of appropriate transducers, and evaluation of their performance for information transmission along nuclear-grade metallic pipes. COMSOL computer simulations were performed to study acoustic wave generation, propagation, and attenuation on pipes. An experimental benchtop system was used to evaluate signal attenuation and spectral dispersion using piezo-electric transducers (PZTs) and electromagnetic acoustic transducers (EMATs). Communication protocols under evaluation consisted on-off keying (OOK) signal modulation, in particular amplitude shift keying (ASK) and phase shift keying (PSK). Tradeoffs between signal power and communication data rate were considered for ASK and PSK coding schemes.

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1.1 Background

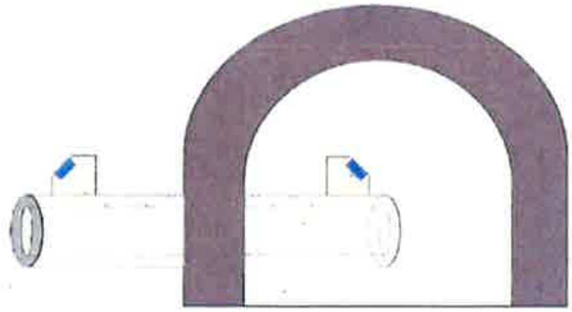


Figure 1 Schematic drawing of proposed communication concept

This project aims to develop and demonstrate methods for transmission of information in nuclear facilities by acoustic means along existing in-place metal pipes. This innovative means of transmitting information overcomes physical hurdles that beset conventional communication methods (both wired and radio frequency (RF) wireless). This technology is intended for those nuclear facilities where wired or wireless RF communication is not feasible (presence of barriers), not reliable (lack of resilience under accident conditions), or not secure (prone to interception). Use of metallic pathways for transmission of information provides an additional level of protection for securing and protecting data streams by eliminating the broadcasting of RF signals outside the facility. While the use of wireless RF signals for the transmission and reception of data in nuclear facilities provides, in principle, greater data transfer rate per unit cost, the presence of physical boundaries presents a major challenge to its actual implementation. The typical nuclear facility for safety reasons (e.g. confinement of radiation and radionuclides) is heavily partitioned and equipment-packed resulting in transmission paths that are highly attenuating for electromagnetic waves. Primary barriers include a containment building's thick reinforced high-strength concrete walls, which in some plant designs have liners (steel plates) on the interior side. Additional security-related concerns related to use of RF exist because of long distance propagation of RF signal outside of nuclear facility boundaries.

1.2 Approach

The approach in this work makes use of in-place process-fluid metal conduits as the backbone of the physical layer of the AC system. Pipes are omnipresent in a nuclear facility given their role of transferring mass and energy between the outside world and the inner workings of the facility. Piping networks will serve as conduits for signals launched as guided acoustic waves. Figure 1 shows a schematic drawing of the proposed acoustic communication concept. Acoustic transducers compatible with harsh operating environment inside the containment structure will be developed, along with efficient digital and analog data communication protocols. The AC system to be developed will be compatible with RF wireless networks due to availability of acoustic to RF transducers.

1.3 Organization

This report describes the results of initial research efforts that focused on modeling of acoustic wave propagation on pipe-like structures and evaluation of On/Off Key (OOK) modulation schemes for information transmission using piezo-electric transducers (PZTs) and electromagnetic acoustic transducers (EMATs) mounted on nuclear-grade pipe. Section 2, Modeling Ultrasonic Waves in Pipe-Like Structures, describes scoping-type calculations to better understand dependence of performance (bandwidth and attenuation) on parameters such as waveform type, transducer type, and transmission medium. In Section 3, Ultrasonic Communication System, the benchtop system that has been assembled for performing tests is described and the results of experiments performed to date on the benchtop system are described.

2. MODELING ULTRASONIC WAVES IN PIPE-LIKE STRUCTURES

The objective of this study is to understand the wave propagation characteristics of ultrasonic waves in pipe-like structures for proper selection of frequency and wave mode to increase the transmission distance of information through metal pathway. There are numerous guided wave modes in a pipe, which include rotational and axially symmetric torsional waves (T(0,m)), axially symmetric longitudinal waves (L(0,m)) and non-axially symmetric flexural waves (L(n,m)), and can be triggered by controlling the position, vibration direction and phase of excitation element (Tang and Wu 2017). The first index implies the harmonic order of circumferential variation, and zero means axially symmetric. The value 1 represents the fundamental modes, and higher order modes are numbered consecutively (Demma 2003). The basic factors of mode selection in this study are dispersion, attenuation, and excitability.

2.1 Selection of Ultrasonic Modes

Dispersion is defined as frequency-dependent wave velocity. Depending on the selected wave mode, the ultrasonic signal may be distorted along propagation distance. Figure 2 shows the dispersion curve of a 3-inch, schedule 40 steel pipe. Typically, symmetric wave modes are less dispersive. For instance, the fundamental torsional mode T(0,1) has the same phase velocity for a range of frequencies while higher order non-symmetric torsional modes have different phase velocities especially in the range of frequencies lower than 300 kHz, which causes significant distortion in wave with distance. A proper transmission of signal through pipe material requires selection of non-dispersive wave modes.

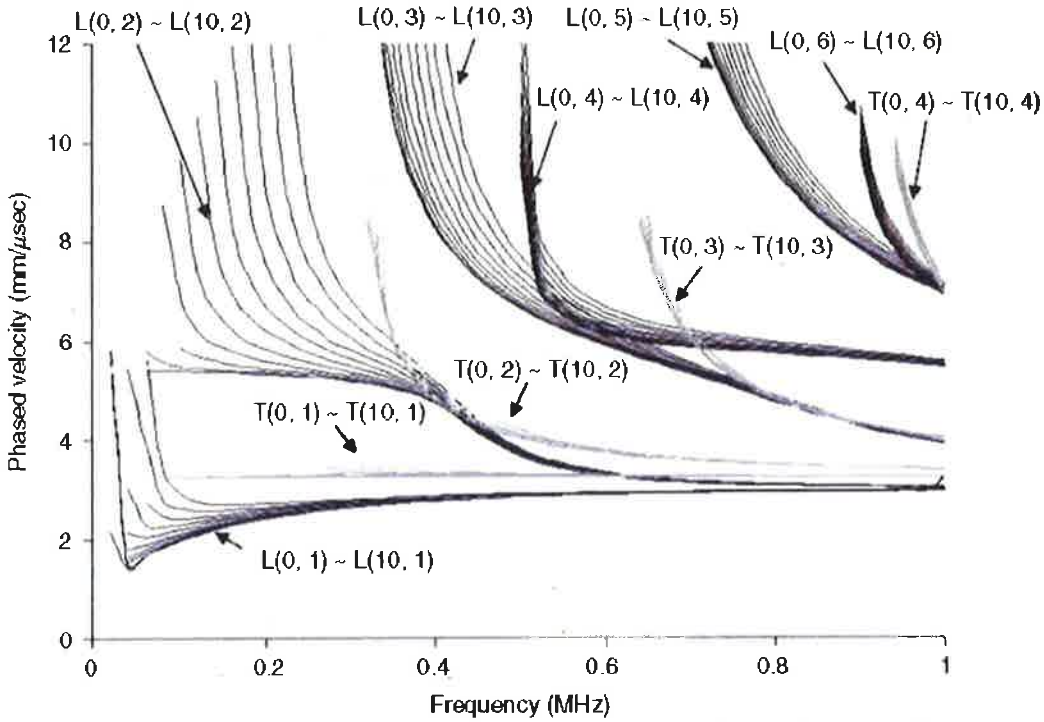


Figure 2 Dispersion curve of 3-inch schedule 40 steel pipe (Rose 2014)

2.2 Excitation of Ultrasonic Modes

The excitation of a particular wave mode is achieved by predetermined phase velocity and frequency to excite a point on the dispersion curve of a specific guided wave mode. In some cases, the traditional bulk wave can be used for generating waves in pipes (Silk and Bainton 1979); however, angle beam method, comb array and EMATs are shown as the most efficient methods in terms of mode selection and control (Rose et al. 1996, Li and Rose 2006). The comparison of different sensor configurations is illustrated in Figure 3. Though the sensor type and configuration are different, the core idea is the same, which is to control and select proper wave mode and frequency. The excitation of axisymmetric modes requires axisymmetric loading, which can be done by axisymmetric placement of transducers. For instance, if all the transducers in a ring positioned on the circumference of pipe are excited simultaneously, an axially symmetric mode is triggered (Lowe et al. 1998).

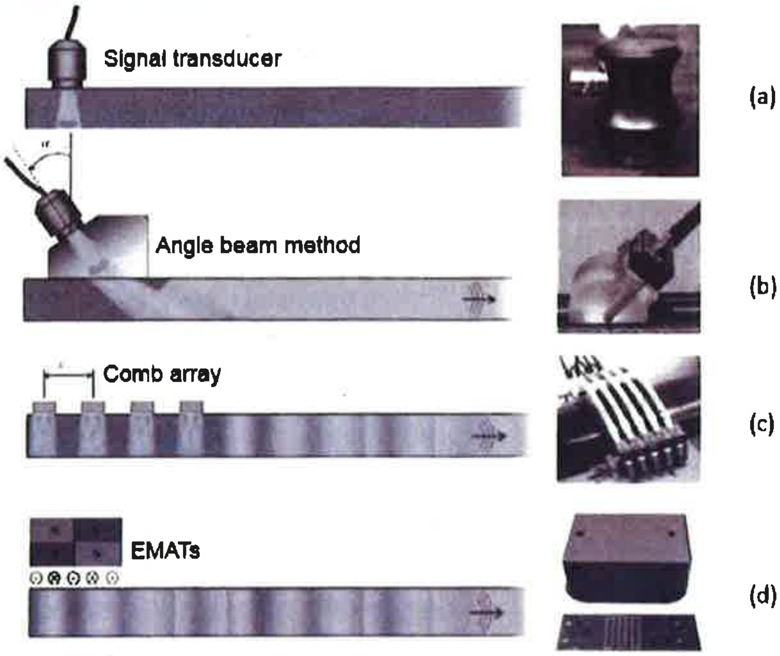


Figure 3 The different sensor configurations for excitation of ultrasonic wave modes (photos on left are courtesy of Rose, Rose 2014 and Pei 2016)

2.3 Numerical Results

In this study, wave propagation characteristics of three wave types in a typical pipe found in nuclear power plants are reported: torsional waves, SH waves, and non-axially symmetric Lamb waves.

2.3.1. Modeling Variables

The major pipe properties that influence the ultrasonic wave propagation are thickness, diameter, material properties, surrounding and internal materials, pipe elbows and the presence of dissimilar materials. The properties selected for the finite element numerical models are shown in Table 1.

Table 1 Pipe dimensions and materials properties (DN65-SCH160)

Thickness (mm)	Diameter (mm)	Young's Modulus (GPa)	Density (kg/m^3)	Poisson's ratio
9.5	73.0	200	8000	0.27

The spatial and temporal discretization of wave propagation problem should be selected such that wave distortion due to numerical error should be minimized. The 3D numerical analysis is fulfilled in COMSOL Multiphysics software. The discretization is selected as linear displacement field, which can not only ensure the accuracy but also reduce the computational time. The pipe model has the mesh size of 2.5 mm using tetrahedral elements. The time step is selected as 1 μs, which corresponds to 200 kHz frequency resolution.

The excitation signal is selected as a chirp signal with different frequency windows as well as a single excitation signal. Figure4a shows the chirp signal in the frequency range of 100-200 kHz, and Figure4b shows the single frequency signal at 5 kHz. When the excitation frequency decreases, its duration increases such that the interference of propagating waves and reflected waves increases.

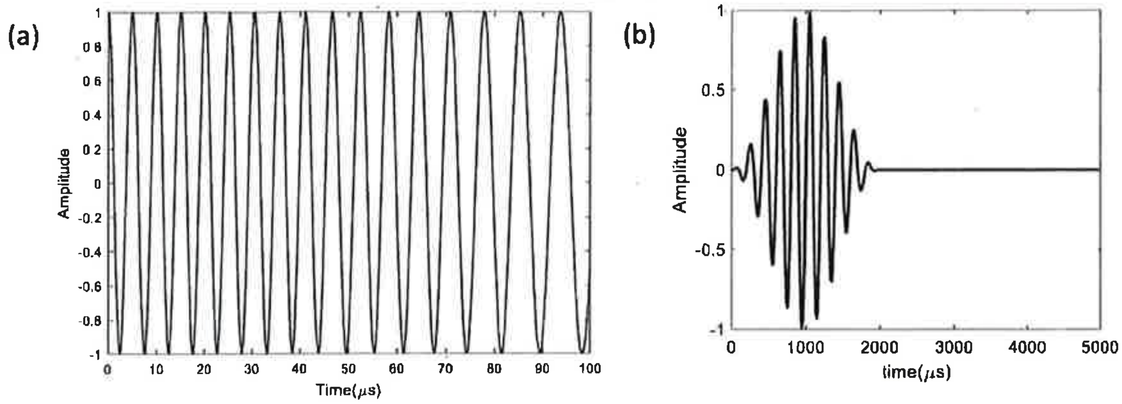


Figure 4 Excitation signals, (a) chiro signal, (b) single frequency signal

In general, the resolution of the chirp signal depends on the duration and sampling frequency. The chirp signal is generated in both quadratic convex and linear modes in this study. Two chirp modes describe two kinds of curves in the positive frequency axis. The quadratic convex model is down-sweep, and the curve between the maximum and minimum frequency is quadratic parabola while linear chirp fades linearly from low to high frequency components. Though the quadratic convex and linear chirp signals are designed with the same frequency bandwidth, duration and sampling frequency, the instantaneous frequency varies linearly in linear mode while nonlinearly in quadratic convex mode.

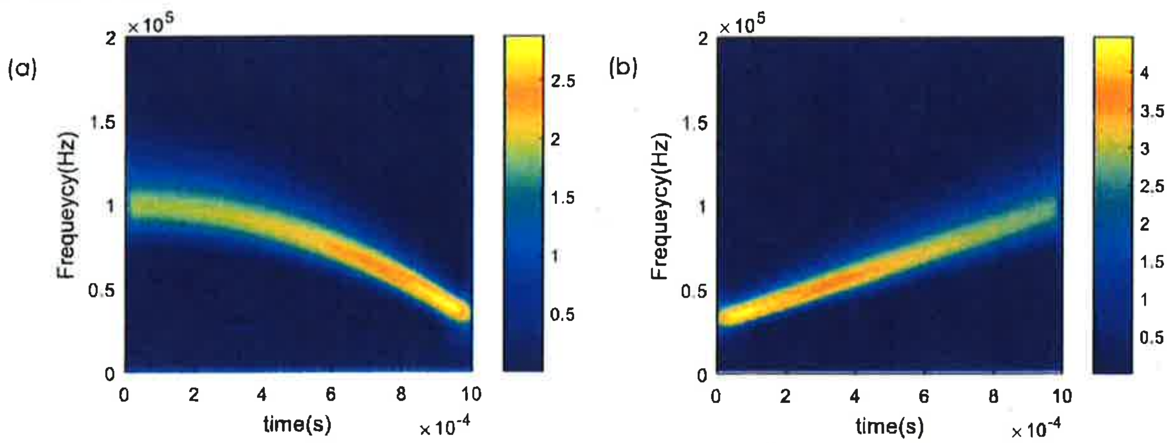


Figure 5 Chirp signals in the range of 30 kHz – 100 kHz, (a) convex mode, (b) linear mode.

To validate the numerical model, pipe geometry and materials similar to an example shown in Rose (2014) are modeled. To prevent the reflection from the boundaries, the excitation signal is placed at the middle of the pipe, and the strain energy density at a particular time is plotted in Figure 5. Both models have similar wave envelope and dispersion at a particular point on the pipe.

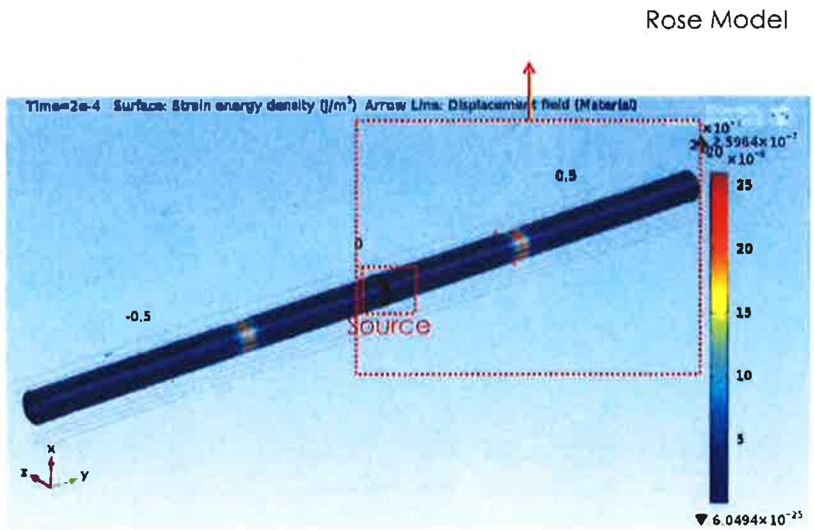


Figure 6 Comparison of numerical model with the Rose (2014) result.

2.3.2. Torsional Waves

First, we studied the torsional waves, which exhibit less dispersion than the other wave modes. The comb-type transducer is considered in the model. In order to generate pure torsional wave, circular array stripe load is applied to the circumference of the pipe with the effective element width as 1.4 mm, and the space between each element as 1.4 mm. Circumferential displacement responses of five typical locations are investigated to show the wave propagation along the pipeline, see in Figure 6. As the purpose of this study is to understand the mechanism of wave propagation, the frequency domain analysis is adequate to show the decay of signal energy. The response signals under quadratic convex and linear chirp are shown in Figure 7. The excitation signals and response signals are compared in the same figure. According to the response signal, the excited frequency signals can be preserved in the frequency domain, especially for low frequency components. With the increase of frequency, the response signals dissipate faster. This phenomenon can be explained by the dispersion curve (Figure 2). For reducing the decay of higher frequency component, the chirp signal in convex mode has been observed as a better option.

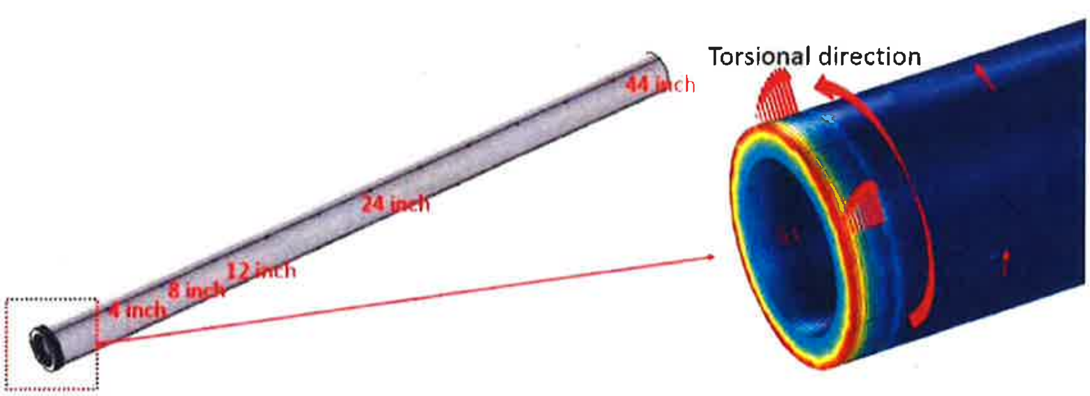
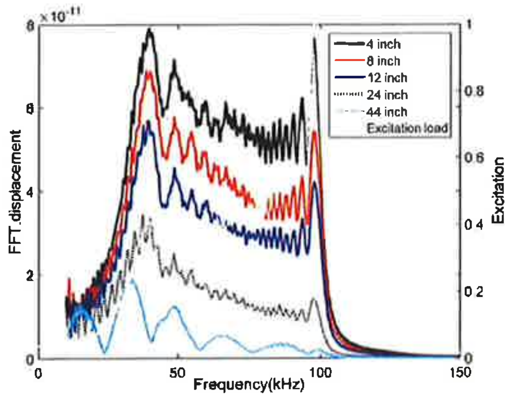
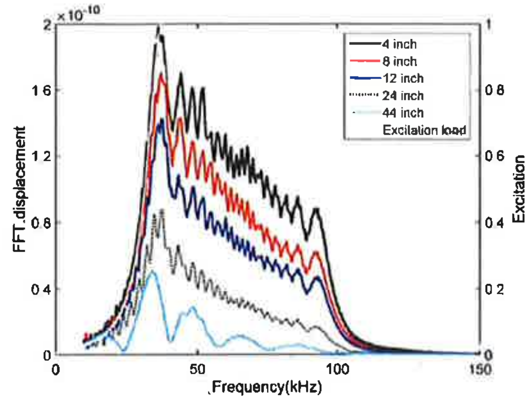


Figure 7 The pipe model and excitation of torsional wave mode.



(a)

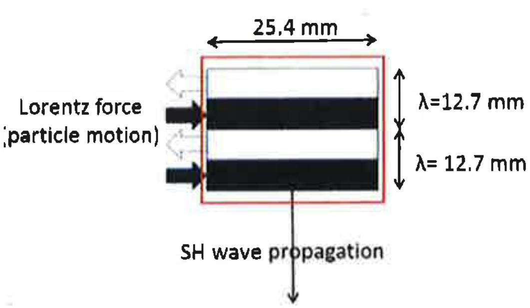


(b)

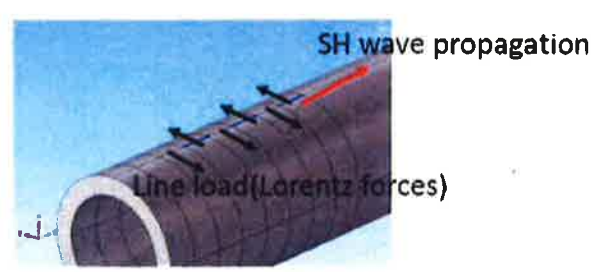
Figure 8 The responses of circumferential displacement at different locations (a) under convex mode and (b) under linear mode.

2.3.3. SH Waves

Shear horizontal (SH) waves are generated by the particle motion in the in-plane direction, while the wave propagation is orthogonal to the particle motion. SH wave mode can be excited by the EMATs. Usually EMAT has two major parts: a magnet and a mender-line coil, which can generate a strong horizontal Lorentz force to cause the particle motion in the tested object. EMAT transducer generates a particular frequency by tuning the length of λ, which is the wavelength of the desired frequency as shown in Figure 9(a). The EMAT design in this figure can be used to excite the frequency of 250 kHz of SH0 wave (Choi 2016). In this model, the Lorentz force is simplified as three pairs of line load as shown in Figure 9(b). Two models are used to show two directions of SH wave propagation: one is along the axial direction, and the other is circumferential direction. Independent from the direction, the response displacement is the same as particle motion. For analyzing the SH wave along axial direction, the model is the same as that used in connection with Figure 6. The only difference is the method of loading. The source function is selected as linear chirp, shown in Figure 4(b). The response signals are shown in Figure 10. The response signals show similar trend as torsional wave. The lower frequency component dissipates less than higher frequencies. However, the response around 78 kHz disappears because the simulated EMAT is tuned as excitation of 92 kHz, which coincides with the second peak frequency. The difference can also be from the error due to simplification of EMAT sensor in the model.



(a)



(b)

Figure 9 (a) EMATs design (b) EMATs simplified model.

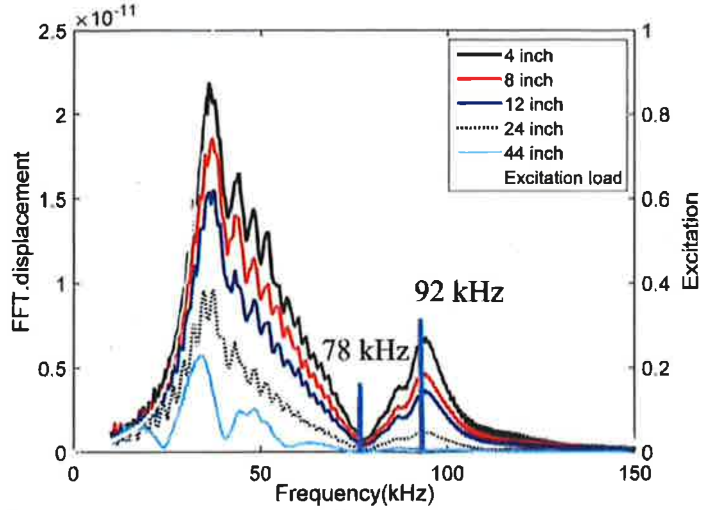


Figure 10 The response signals due to axial SH wave mode.

To understand the SH wave propagation behavior better, we also present one larger model to show SH wave propagating in the circumferential direction. The dimension of the model is from Rose (2014), which is shown in Figure 11. In this model, frequency of EMAT is tuned as 93 kHz, and also the tone burst signal with 100 kHz is applied. The comparison of excitation signal and response is shown in Figure 12. The frequency component of excitation can be preserved, while only a small shift toward the lower frequency is observed. Therefore, after proper tuning, the SH wave can also preserve its frequency and travel over long range.

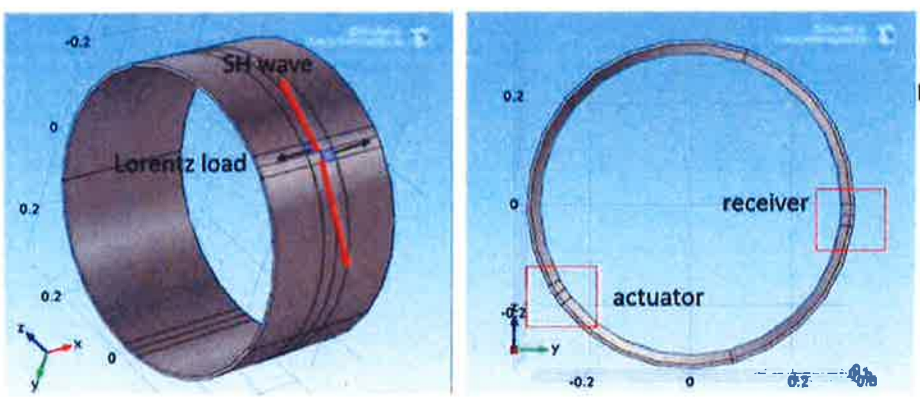


Figure 11 The model of circumferential SH wave propagation.

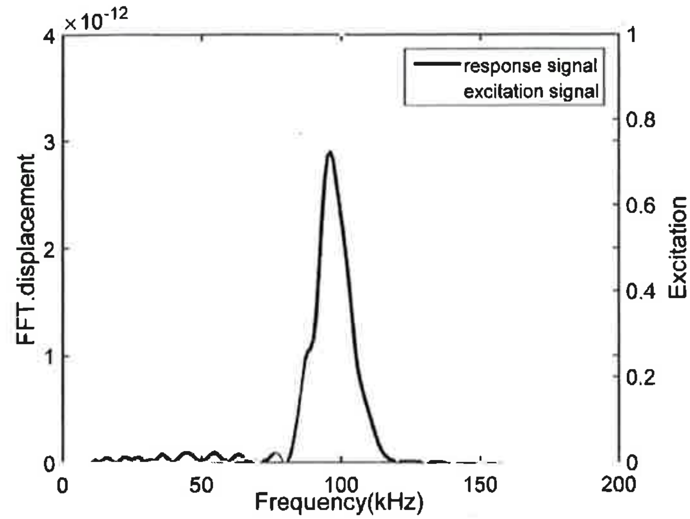


Figure 12 The response signal due to circumferential SH wave mode.

2.3.4. Non-axisymmetric Waves

Non-axisymmetric waves are excited by a direct transducer contact on a finite area on the pipe, which is the superposition of axisymmetric longitudinal modes L(0,n) and non-axisymmetric modes F(m,n) with different amplitudes and phase velocities (Li and Rose 2006). In the numerical model, the point load excitation is adopted. The model is the same as that used in connection with Figure 6; the linear chirp is the loading function, which is the same as that shown in Figure 4(b). The point load could trigger more complex waves including longitudinal, torsional, and flexural modes. The flexural wave is salient due to non-axisymmetric motion of particles. The response signals in flexural mode are distorted after they travel a short distance as seen in Figure 13. Unlike waves in torsional and SH modes, the non-axisymmetric waves in flexural mode cannot preserve the source information. Instead, the response signals show a more complex behavior.

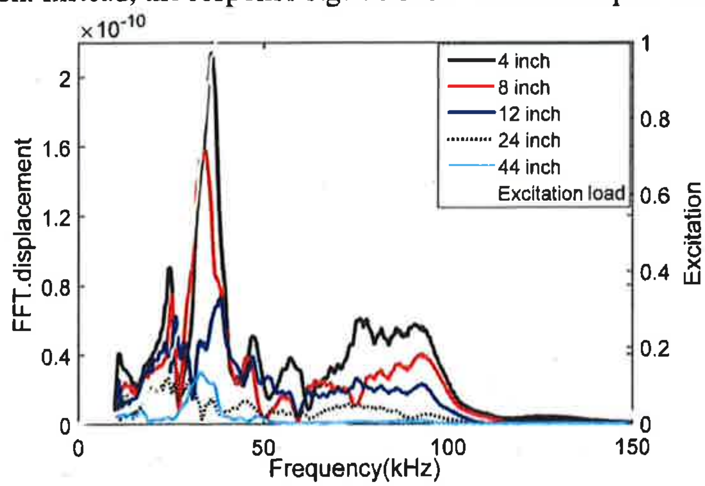


Figure 13 The response signal in non-axisymmetric waves mode.

2.3.5. Influence of Elbow on Ultrasonic Wave Propagation

Mode conversion occurs when an ultrasonic waves passes through a bended pipe (Nishino et al. 2006). In order to understand the influence of elbow on the torsional wave propagation, the pipe model with 90 degrees elbow is modeled as shown in Figure 14(a). The material properties and dimension of the pipe are still the same as those listed in Table 1. The Hanning windowed tone burst signal with the frequency of 30 kHz is introduced as the loading function. In this case, time domain analysis is used to better describe wave propagation in the pipeline with elbow. The Figure 14(b) shows the torsional wave propagation as it propogates through the elbow. After interacting with the elbow, the wave front is distorted due to the reflection and transmission by the elbow; and mode conversions occur simultaneously. The loading function together with the response signals of receiver A, B and C are shown in Figure 15. The peak frequency of the response signal shifts away from 30 kHz to form another two frequency modes. The propagating waveform interferes with the reflected waveform. Therefore, a window was defined to reduce the influence of backward reflection of the waveform. The defined window is marked in Figure 15(a). The elbow influence is illustrated more clearly in Figure 16. As shown in Figure 16(b), the response signal of receiver A has the same peak frequency as excitation load, while the peak frequencies of receiver B and C are shifted. This phenomenon shows that wave mode conversion happens after the wave travels through the elbow, which has been verified by Nishino et al (2011).

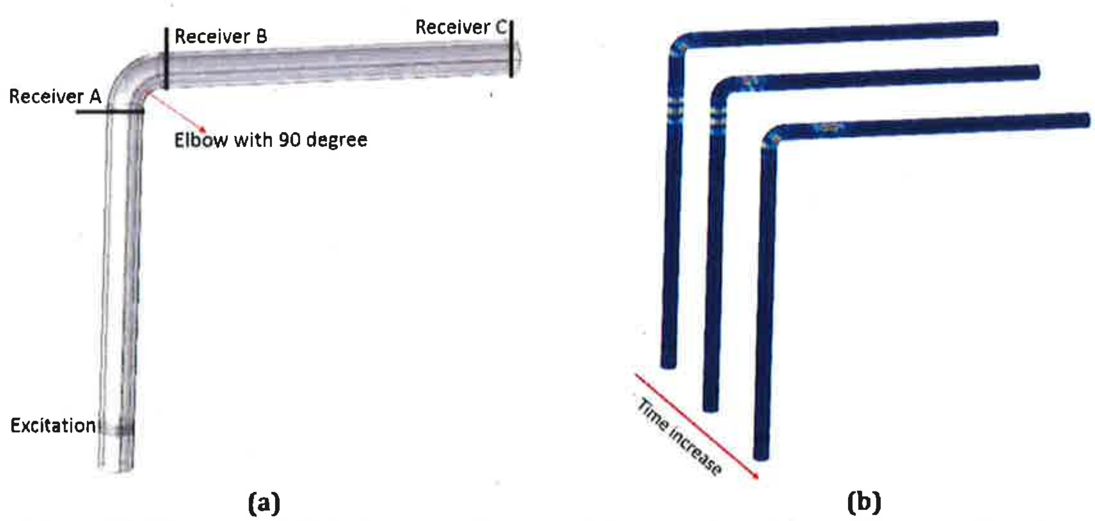
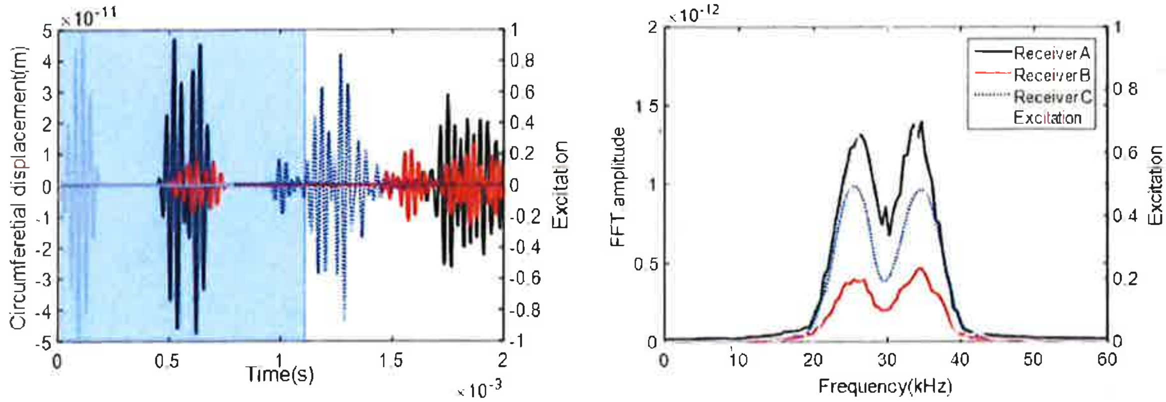
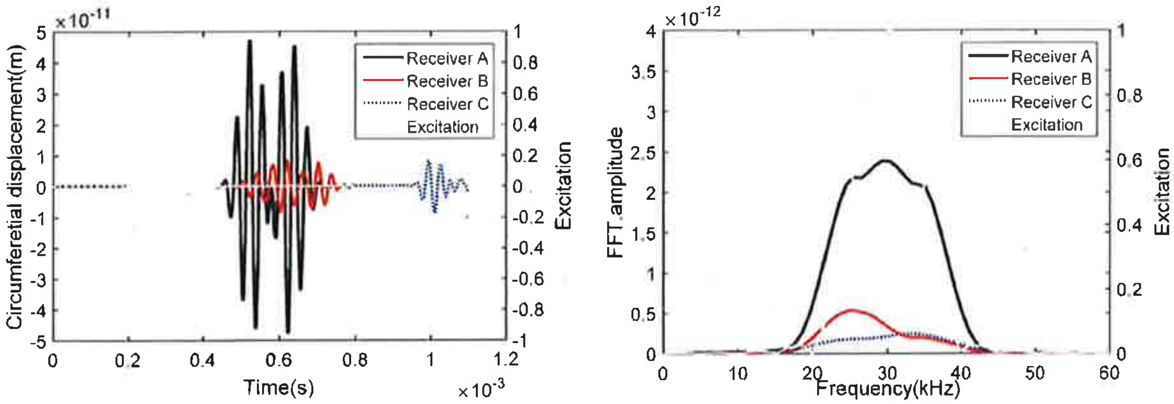


Figure 14 (a) The model of pipeline with elbow (b) wave group propagation near the elbow.



(a) (b)

Figure 15 The response signals of the model of pipeline with elbow (a) in time domain (b) in frequency domain.



(a) (b)

Figure 16 The windowed response signals (a) in time domain (b) in frequency domain.

2.4 Discussion

Though any wave mode can be used for transmitting waves in pipes by comprehensive tuning, it is difficult to identify and restore the excitation signals based on the non-axisymmetric waves in flexural modes. Therefore, axisymmetric modes are preferable because their acoustic distribution in the structure is relatively simple. For mutual communication of wave information, dispersion free wave modes (torsional and SH waves) allow the wave to propagate over longest distances with minimum distortion.

3. ULTRASONIC COMMUNICATION SYSTEM

3.1. Experiment setup

Research efforts under this subtask have focused preliminary on evaluating the performance bounds on information transmission along a pipe using a pair of commercially available PZTs and EMATs. For the initial experimental studies, a five-foot long schedule-160 stainless steel pipe with 2.375" outer diameter and 0.344" wall thickness was chosen as the medium for evaluation of acoustic signal transmission. Dimensions of this pipe closely resembles those of CVCS pipe which penetrate through reactor containment wall. Olympus paintbrush 500KHz PZTs mounted on angled wedges were chosen for initial testing. The lowest frequency for commercially available transducers of this type is 500KHz. As discussed in the previous section, a lower frequency results in lower signal attenuation and allows for more power-efficient operation of the communication system. Schematic drawing and a photograph of the benchtop test setup are shown in Figure 17.

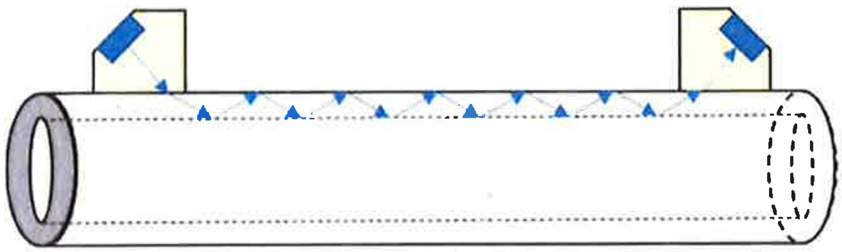


Figure 17 Experimental setup for signal transmission using symmetric arrangement of refracted wave PZT on schedule-160 stainless steel pipe.

The PZT angled beam transducers use the principles of refraction and mode conversion to produce refracted shear or longitudinal waves in the test material. The incident angle necessary to produce a desired refracted wave can be calculated from acoustic's Snell's Law

$$\frac{\mathrm{Sin}\theta_i}{C_i} = \frac{Sin\theta_{rl}}{C_{rl}} = \frac{Sin\theta_{rs}}{C_{rs}} \tag{1}$$

where

θ_i : Incident Angle of the Wedge
θ_{rl} : Angle of the Refracted Longitudinal Wave
θ_{rs} : Angle of the Refracted Shear Wave
C_i : velocity of the incident Material (Longitudinal Wave)
C_{rl} : material sound velocity (longitudinal)
C_{rs} : velocity of the test material (Shear)

Acoustic wave refraction of a longitudinal wave excited by an angle beam transducer is shown in Figure 18. Figure 19 displays diagrams of relative intensities of longitudinal and shear waves in stainless steel generated via refraction from an acrylic wedge. For the tests conducted in this project, the angle of the wedge is 33°, which results in the highest degree of coupling into refracted shear wave in the pipe used in these tests. The distance for signal transmission was fixed at 5 feet, which can be considered as the minimum distance required for transmission of signals along a pipe penetrating through the containment building wall.

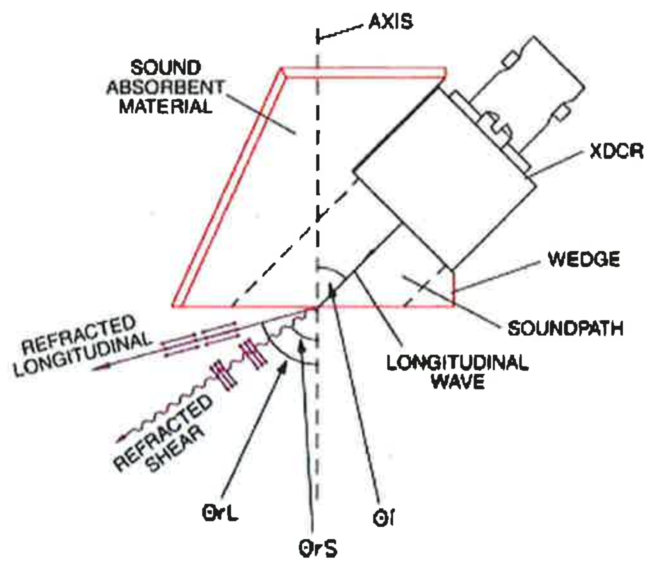


Figure 18 Snell's Law of angle beam transducer.

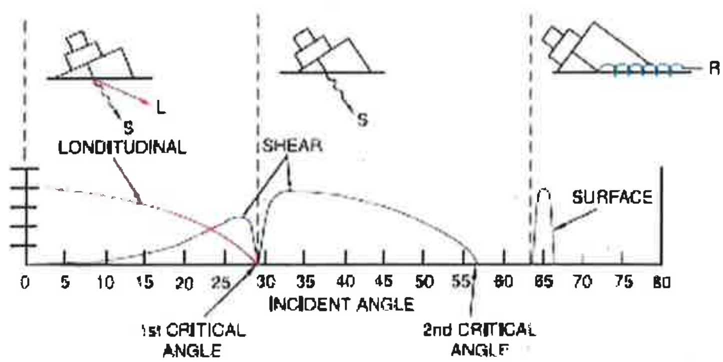


Figure 19 Relative amplitude of wave modes

3.2. Modulation method

Preliminary evaluations have been conducted of frequency modulation (FM) and on-off keying (OOK) modulation. The objective is to determine optimal modulation scheme for transmission of signal under the constraint of limited signal generator power.

3.2.1 Frequency distortion

Feasibility of frequency modulation (FM) scheme for information transmission was evaluated using spectral dispersion characteristics of pulses of different temporal duration. Figure 20 demonstrates that transmitting a narrowband 500KHz signal with 50µs duration results in more spectral dispersion, as compared to the case when the pulse duration is 100µs. Given the amount of spectral distortion and dispersion observed in preliminary tests, we conclude that FM not likely going to be the optimal coding scheme in this project.

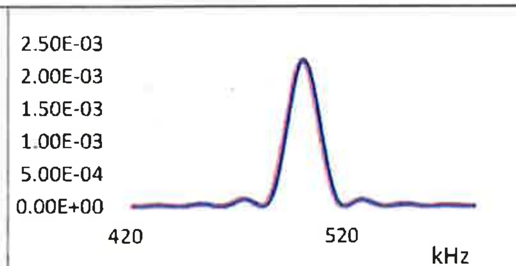
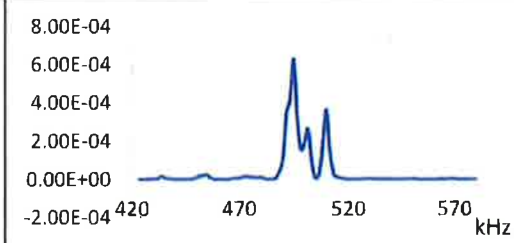
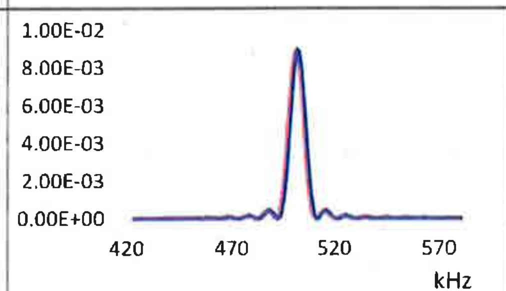
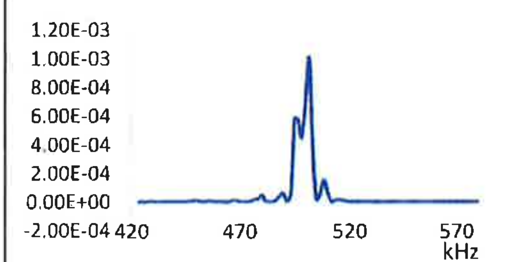
Pulse Time	Transmitted Signal Spectrum	Received Signal Spectrum
50µs		
100µs		

Figure 20 Spectral dispersion and distortion of narrow band pulses of different temporal duration

3.2.2 ASK modulation

Amplitude shift keying (ASK) is a common implementation of on-off keying (OOK) communication protocol. The principle of ASK is to code signal s(t) as

$$s(t) = \begin{cases} 1 & \text{logic } 1 \\ 0 & \text{logic } 0 \end{cases}$$

An example of 50µs bit pulse duration is shown in Figure 21. Transmitted binary message "101." Transmitted and received signals are overlaid by subtracting time-of-flight from received signal. Amplitudes of transmitted and received signals are not to scale.

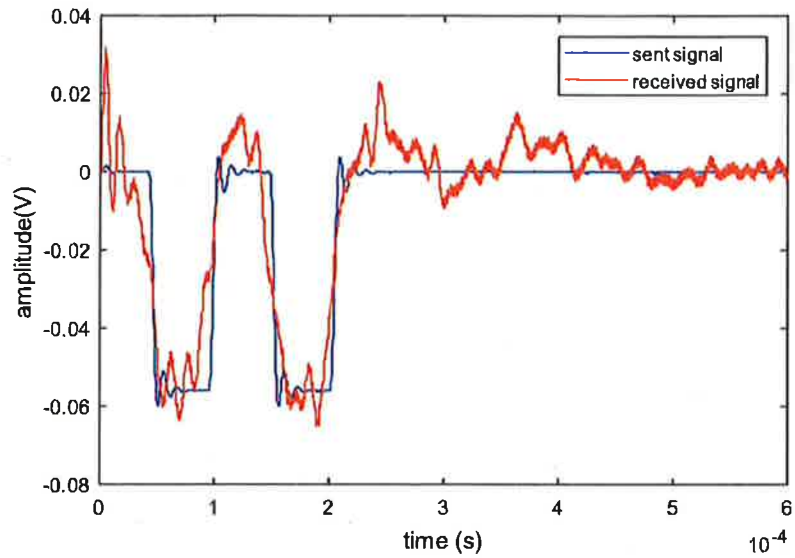


Figure 21 Example of ASK modulation with 50 micro-s bit pulse duration. Transmitted and received signals are overlaid with amplitudes not to scale.

More complicated ASK waveforms are shown in Figure 22. In the top panel, bit pulse length is 50μs. The transmitted binary message is "11001011." In the bottom panel, the binary signal is "1101011"

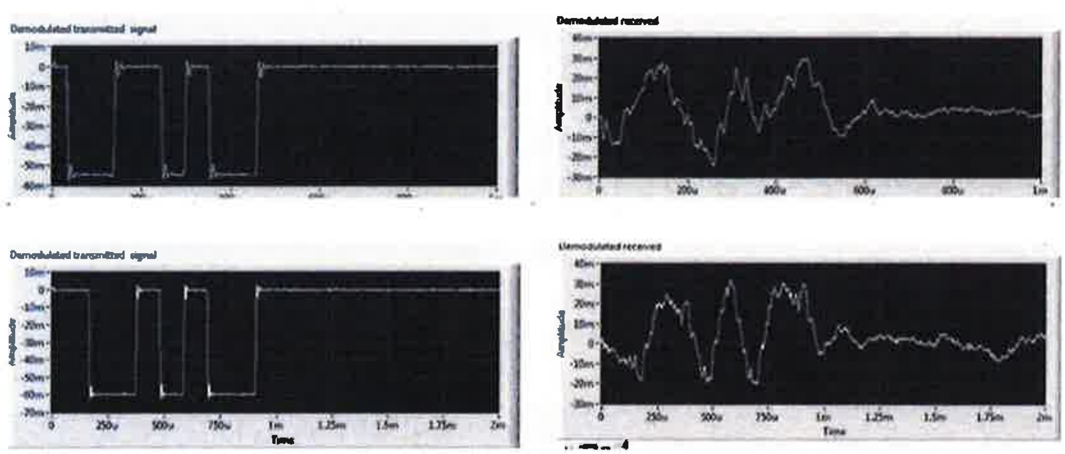


Figure 22 Examples of ASK signals (left - transmitted, right - received).
Top panel: binary signal "11001011".
Bottom panel: binary signal "1101011".

3.2.3 PSK modulation

The modulation method of the phase shift keying (PSK) is almost the same as that of the ASK. The difference is that the s(t) signal is the imaginary part of IQ signal, and '1' represent 'logic 1'; '-1' represent 'logic 0'. Figure 23 gives an example of PSK signal modulation with bit pulse duration of 50μs. Transmitted binary signal is "101."

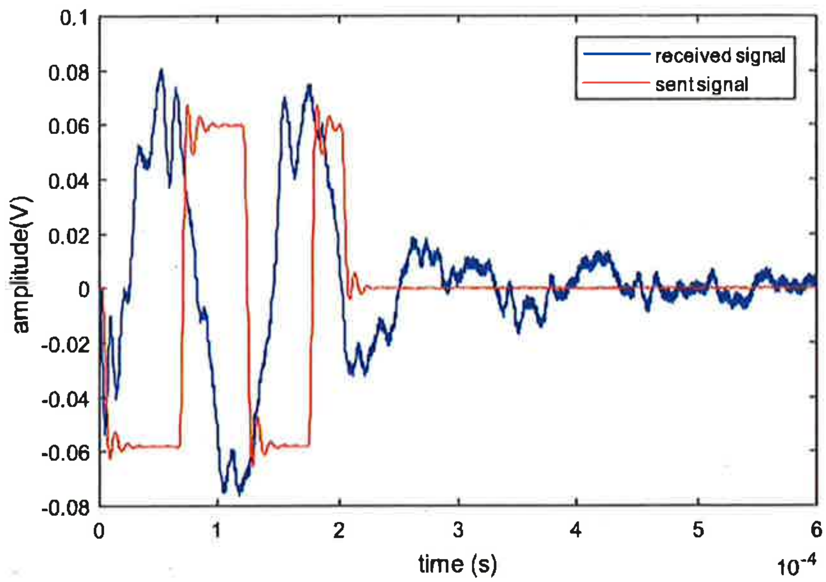


Figure 23 Example of PSK signal with 50 micro-s bit pulse duration.

Additional examples of more complex PSK coded sequences are shown in Figure 24. Panel on the left shows transmission and reception of binary signal "1100." Panel on the right shows transmission and reception of binary signal "1001."

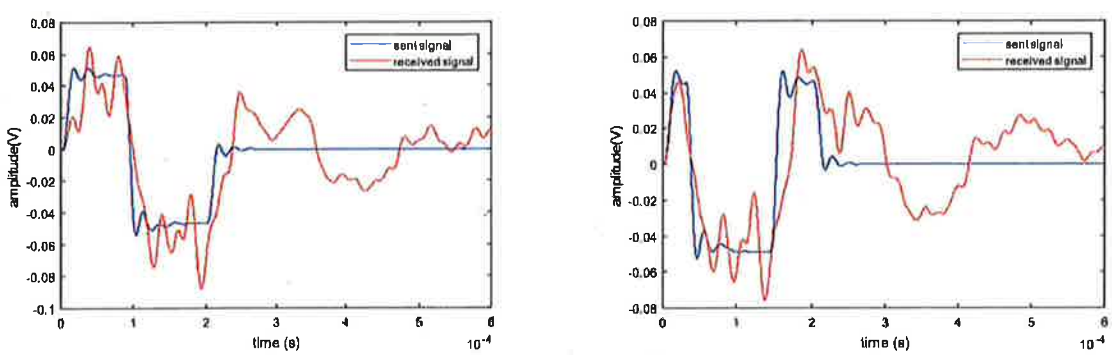


Figure 24 Example of PSK modulation. Left: binary signal "1100". Right: binary signal "1001".

3.3. Signal transmission with EMAT

As described in previous report, EMAT transducers generate ultrasonic waves in electrically conductive materials by Lorentz force, by electro/magnetostrictive effect, or by a combination thereof. Acoustic waves are generated directly within the electrically conducting medium instead of inside the transducer as with piezoelectric transducers. The Lorentz force is caused by interaction represent 'logic 0'. Figure 23 gives an example of PSK signal modulation with bit pulse duration of 50μs. Transmitted binary signal is "101."

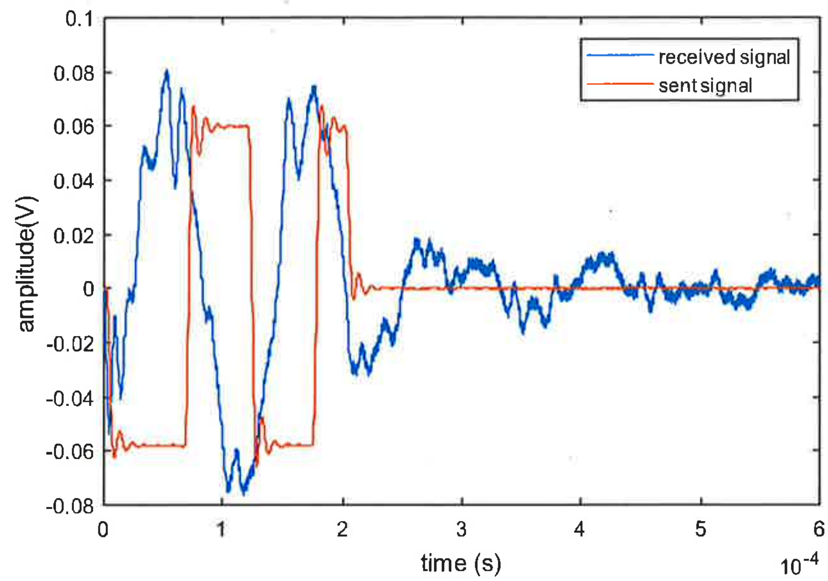


Figure 23 Example of PSK signal with 50 micro-s bit pulse duration.

Additional examples of more complex PSK coded sequences are shown in Figure 24. Panel on the left shows transmission and reception of binary signal "1100." Panel on the right shows transmission and reception of binary signal "1001."

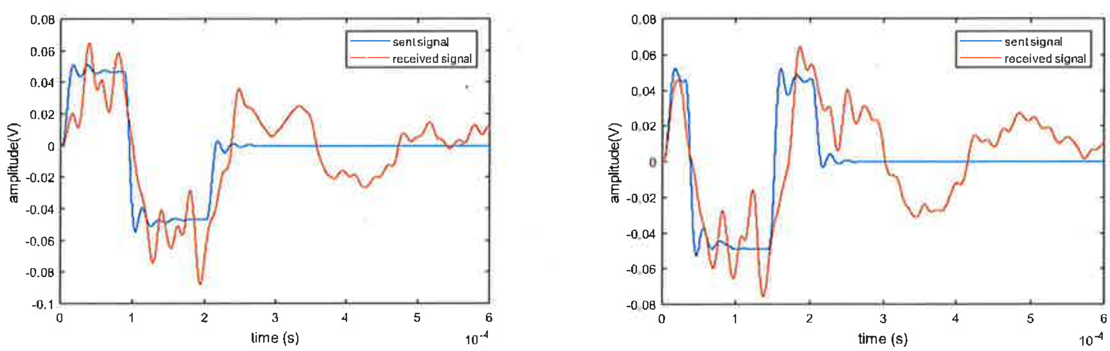


Figure 24 Example of PSK modulation. Left: binary signal "1100". Right: binary signal "1001".

3.3. Signal transmission with EMAT

As described in previous report, EMAT transducers generate ultrasonic waves in electrically conductive materials by Lorentz force, by electro/magnetostrictive effect, or by a combination thereof. Acoustic waves are generated directly within the electrically conducting medium instead of inside the transducer as with piezoelectric transducers. The Lorentz force is caused by interaction between the electric current (current density J) which is inducted through the eddy current coil and the magnetic flux (B_0). The direction and intensity of the force $\overline{F}_L$is determined by the vector equation:

$$\overline{F}_L = \overline{J} \times \overline{B}_0$$

The incident angle of SH-EMAT is determined as

$$\sin\alpha = \lambda / \lambda_s$$

Where λ is the wavelength of the SH- wave and λ_s is the unit dimension of the magnet. For the initial tests, an Innerspec EMAT generating SH waves was used as transmitter and a PZT was used as receiver. Because of the RF coupling associated with EMAT excitation, a time delay was introduced in order to avoid interference of the RF pulse with the test signal. The optimum angle of the PZT receiver was obtained by using a variable angle wedge. Furthermore, the optimum carrier frequency was selected based on maximization of the received signal amplitude transmitted along the pipe. Figure 25 displays the setup of signal transmission from EMAT to PZT.

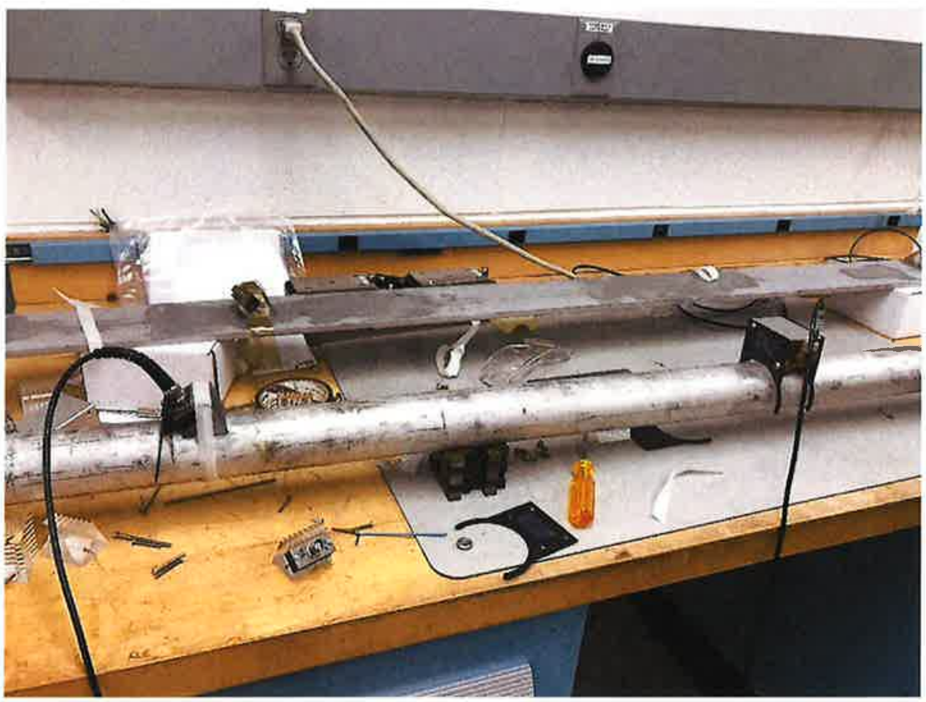


Figure 25 EMAT to PZT signal transmission setup.

Examples of signal transmission are shown in Figures xx. Spectrum of transmitted single pulse signal from EMAT to PZT is shown in Figure 26. Time-domain waveform of a signal transmitted from EMAT to PZT is shown in Figure 27.

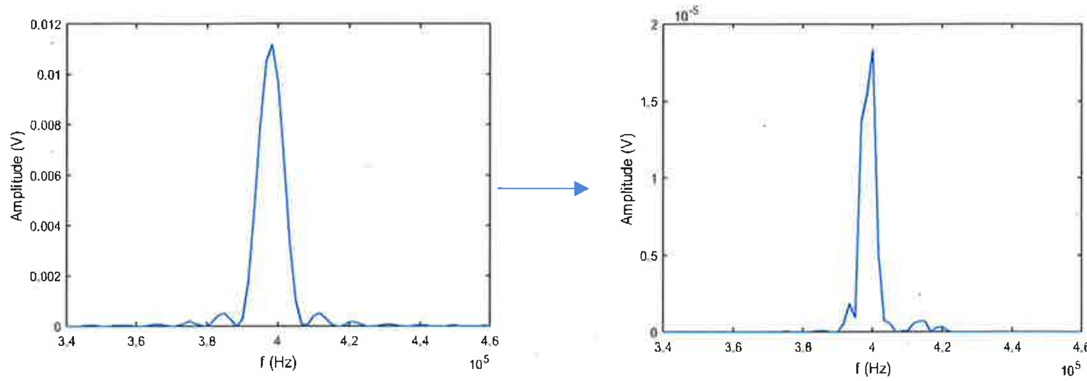


Figure 26 Spectrum of signal transmitted with EMAT (left) and received with PZT (right).

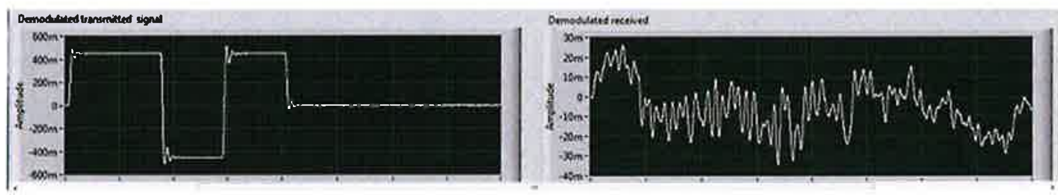


Figure 27 Example of time-domain waveform transmitted from EMAT to PZT.

4. CONCLUSION

Based on preliminary results of signal transmission, OOK is the preferred modulation scheme for information transmission. Information transmission using both ASK and PSK schemes will be further explored in the next quarter. Benchmarks for information transmission rate, signal to noise ratio, and bit error rate will be established. The studies will consider tradeoffs between signal to noise ratio of received signals and information transfer rates. For a fixed pulse amplitude, longer pulse duration results in higher power of the transmitted signal, which leads to higher signal to noise ratio of the received signal. However, increasing temporal duration of the signal decreases the rate of information transfer.

5. REFERENCES

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